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On the Social Traits of Luminous Blue Variables

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ABSTRACT

In a recent paper, Smith & Tombleson (2015) state that the Luminous Blue Variables (LBVs) in the Milky Way and the Magellanic Clouds are isolated; that they are not spatially associated with young O-type stars. They propose a novel explanation that would overturn the standard view of LBVs. In this paper we test their hypothesis for the LBVs in M31 and M33 as well as the LMC and SMC. We show that in M31 and M33, the LBVs are associated with luminous young stars and supergiants appropriate to their luminosities and positions on the HR Diagram. Moreover, in the Smith and Tombleson scenario most of the LBVs should be runaway stars, but the stars' velocities are consistent with their positions in the respective galaxies. In the Magellanic Clouds, those authors' sample was a mixed population. We reassess their analysis, removing seven stars that have no clear relation to LBVs. When we separate the more massive *classical* and the *less luminous* LBVs, the classical LBVs have a distribution similar to the late O-type stars, while the less luminous LBVs have a distribution like the red supergiants. None of the confirmed LBVs have high velocities or are candidate runaway stars. These results support the accepted description of LBVs as evolved massive stars that have shed a lot of mass, and are now close to their Eddington limit.

Subject headings: galaxies:individual(M31,M33,LMC,SMC) –stars: variables: S Doradus – stars:massive – supergiants

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1. Introduction – Crucial Distinctions Among LBVs

Luminous Blue Variables (LBVs) or S Doradus variables have attracted attention in recent years for two mutually independent reasons. Normal hot-star winds cannot account for sufficient mass loss (Fullerton et al. 2006), thus another form of mass loss, perhaps in LBV events, is required for them to become WR stars, see also Humphreys & Davidson (1994). Second, the non-terminal supernova impostors resemble extreme LBV outbursts (Van Dyk & Matheson 2012) and certain types of supernovae were observed to have experienced prior high mass loss events that have been likened to LBVs.

Unfortunately, serious confusion has arisen because disparate objects are often mixed together and collectively called “LBVs.” In a recent paper, Smith & Tombleson (2015) argue that LBVs are not generically associated with young massive stars. They suggest that LBVs gained mass from more massive companions in interacting binary systems and subsequently moved away from their birth sites when the companions became supernovae. This would contradict traditional views in which evolved massive hot stars experience periods of enhanced mass loss, in transition to a WR star or a supernova. Their argument is based on their failure to find LBVs closely associated with young O-type stars in the Milky Way and the Magellanic Clouds. As we explain in Section 4.2 however, Smith and Tombleson’s statistical sample is a mixed population and with at least three physically distinct types of objects. When they are separated, the statistics agree with standard expectations. We mention this example because it illustrates the need to distinguish between giant eruptions, classical LBVs, less-luminous LBVs, LBV candidates, and others such as B[e] stars that occupy the same part of the HR diagram. In this paper we explore those distinctions.

Since there are numerous misunderstandings in this subject, a careful summary of the background is useful. LBV/S Dor variables are *evolved massive stars, close to the Eddington limit, with a distinctive spectroscopic and photometric variability*. There are two classes with different initial masses and evolutionary histories as we explain later. In its quiescent or normal state, an LBV spectrum resembles a B-type supergiant or Of-type/WN star. During the “eruption” or maximum visible light stage, increased mass loss causes the wind to become optically thick, sometimes called a pseudo-photosphere, at $T \sim 7000\text{--}9000$ K with an absorption line spectrum resembling an F-type supergiant. Since this alters the bolometric correction, the visual brightness increases by 1–2 magnitudes while the total luminosity remains approximately constant (Wolf 1989, Humphreys & Davidson 1994 and numerous early references therein) or may decrease (Groh et al. 2009). Such an event can last for several years or even decades.

There are two recognized classes of LBV/S Dor variables based on their position on the HR Diagram (Humphreys & Davidson 1994). The *classical LBVs*, with bolometric magni-

tudes between -9.7 and -11.5 ($\log L/L_\odot \gtrsim 5.8$) have clearly evolved from very massive stars with $M_{\text{ZAMS}} \gtrsim 50 M_\odot$. Their high mass loss prevents them from becoming red supergiants (Humphreys & Davidson 1979). The *less luminous* LBVs with $M_{\text{Bol}} \simeq -8$ to -9.5 mag had initial masses in the range ~ 25 to $40 M_\odot$ or so, and can become red supergiants.

Some factor must distinguish LBVs from the far more numerous ordinary stars with similar T_{eff} and L , and L/M is the most evident parameter. LBVs have larger L/M ratios than other stars in the same part of the HR Diagram. Their Eddington factors $\Gamma = L/L_{\text{Edd}}$ are around 0.5 or possibly higher.¹ This is not surprising for the very massive classical LBVs. But how can the less luminous LBVs have such large L/M ratios? The simplest explanation is that they have passed through a red supergiant stage and moved back to the left in the HR diagram (Humphreys & Davidson 1994). Meynet & Maeder (2005) showed that stars in the $22 - 45 M_\odot$ initial mass range, evolving back to warmer temperatures, will pass through the LBV stage. Recent evolutionary tracks, with mass loss and rotation (Ekstrom et al. 2012), show that these stars will have shed about half of their initial mass. Having lost much of their mass, they are now fairly close to $(L/M)_{\text{Edd}}$. Although empirical mass estimates are uncertain, the low luminosity LBVs are close to their Eddington limit with $\Gamma \approx 0.6$ (Vink 2012). Hence *the evolutionary state of less-luminous LBVs is fundamentally different from the classical LBVs*.

To illustrate this, in Figure 1 we show the evolution of L/M for two different masses representing the two LBV/S Dor classes. It shows a simplified Eddington factor, $\Gamma_s = (L/L_\odot)/(43000M/M_\odot)$, as a function of time in four evolution models reported by Ekstrom et al. (2012) for rotating and non-rotating stars with $M_{\text{ZAMS}} = 32$ and $60 M_\odot$. The 32 and $60 M_\odot$ models have $\log L \sim 5.6$ and 6.0 , respectively, when they are in the LBV instability strip (see Figs. 2 and 3). Three critical evolution points are marked in the figure: (1) The end of central H burning, (2) the farthest major excursion to the red side of the HR Diagram, and (3) the end of central He burning. For the $60 M_\odot$ star, $\Gamma_s \gtrsim 0.5$ as it leaves the main sequence, but the $32 M_\odot$ star must pass through yellow and/or red supergiant stages before its Γ_s reaches 0.5. Of course, these examples depend on the input parameters and assumptions of the models. Other recent evolution models with mass loss and rotation generically agree on the main point stated here, see for example, Chen et al. (2015)

Therefore we should expect that only the classical LBVs should be associated with young objects such as O-type stars. The less luminous LBVs, more than 5 million years old, will have moved 50 - 100 pc and are also old enough for their neighbors to evolve out of the O star class. Among other results in this paper, we find that the data agree with this

¹ For example, P Cyg and AG Car have $\Gamma \approx 0.5$ (Vink & de Koter 2002; Vink 2012).

expectation.

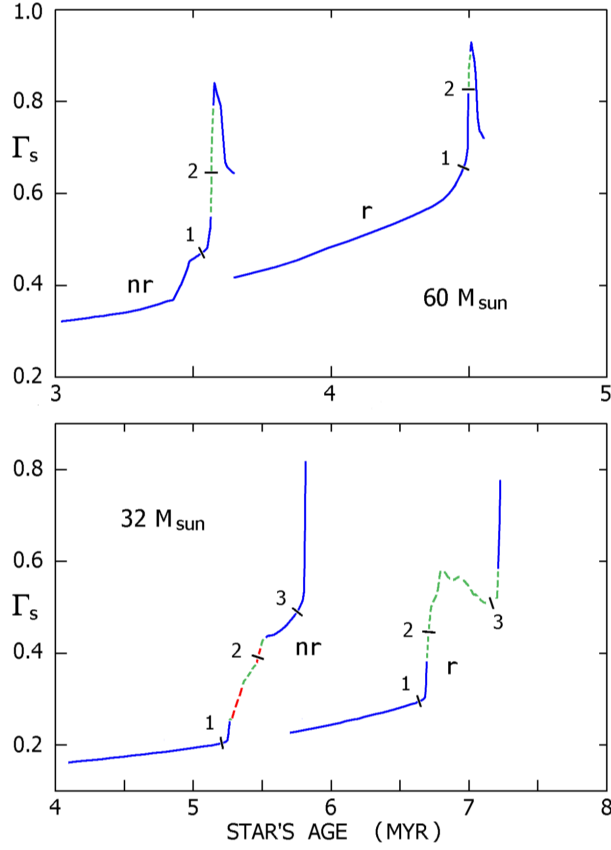


Fig. 1.— The Eddington parameter Γ_s (see text) as a function of time for two initial masses, 32 and 60 M_{\odot} , with (r) and without rotation (nr). The initial rotation velocities in the models, respectively, are 306 and 346 km s^{-1} . Marked evolution points are (1) end of central H-burning, (2) coolest value of T_{eff} , and (3) end of central He-burning. Blue curves represent stages where $T_{eff} > 10000$ K, red indicates $T_{eff} < 4500$ K, and intermediate-temperature stages are shown in green. The dashed segments indicate yellow and red supergiant stages where low ionization and other factors make Γ_s ineffective.

One of the distinguishing characteristics of LBV/S Dor variability is that during quiescence or minimum light, the stars lie on the S Dor instability strip first introduced by Wolf (1989) and illustrated here in Figures 2 and 3. The more luminous, classical LBVs above the upper luminosity boundary have not been red supergiants, while those below are post-red supergiant candidates. Thus LBVs with very different initial masses and different evolutionary histories occupy the same locus in the HR Diagram.

No single cause is generally accepted as the origin for the LBV/S Dor enhanced mass

loss/optically thick wind events. Most proposed explanations invoke the star’s proximity to its Eddington limit due to previous high mass loss. Proposed models include an opacity-modified Eddington limit, subphotospheric gravity-mode instabilities, super-Eddington winds, and envelope inflation close to the Eddington limit (see §5 in Humphreys & Davidson 1994, Glatzel 2005, Owocki & Shaviv 2012, and Vink 2012).

In a *giant eruption*, represented by objects like η Car in the 1840’s and P Cygni in the 1600’s, the star greatly increases its total luminosity with an increase in its visual magnitude typically by three magnitudes or more. Giant eruptions should not be confused with the normal LBV/S Dor variability described above. The energetics of the outburst and what we observe are definitely different. Unfortunately, many authors do not make the distinction especially with respect to the SN impostors and the progenitors of Type IIn supernovae.

Few confirmed LBVs are known in our galaxy due to their rarity, uncertainties in distance, and the infrequency of the LBV “eruption”. There are only six confirmed LBVs in the LMC and one in the SMC. Thus, even the Magellanic Clouds do not provide a large enough sample to confidently determine their relative numbers and group properties relative to other massive star populations. In this paper we examine the spatial distribution of the LBVs and candidate LBVs in M31 and M33 based on our recent discussion of the luminous stars in those galaxies which included the discovery of a new LBV in M31 (Humphreys et al. 2013, 2014b, 2015). In the next section we show that the majority of these LBVs are found in or near associations of young stars, and although spectra are not available for nearby neighbors, their magnitudes and colors support the classification of most of them as hot supergiants.

It must be emphasized that LBVs are *evolved* massive stars. We should not necessarily expect to find them closely associated with young O stars. This is especially true for the less luminous LBVs. The appropriate comparison population should be those supergiants found near the quiescent temperature and luminosity of the LBVs on the HR Diagram; that is, the evolved massive stars presumably of similar initial mass. In the Milky Way (Section 3), it is equally important that they be at the same distance. The Smith and Tombleson Magellanic Cloud sample was a mixed population; they combined the classical LBVs with $\log L/L_{\odot} \geq -5.8$ and the less luminous LBVs. In Section 4 we reassess their analysis separating the LBVs into the two groups based on their positions on the HR Diagram. Their spatial distribution and their kinematics lead to significantly different conclusions which are summarized in the last section.

2. The LBVs in M31 and M33

The LBVs in M31 and M33 were originally known as the Hubble-Sandage variables. In their paper on the "brightest variables", Hubble & Sandage (1953) indentified one star in M31 (V19 = AF And) and four in M33 (Vars. A, B, C, and 2) based on their long term light curves from ≈ 1920 's to 1950 ². There are now five confirmed LBVs in M31: AF And (Hubble & Sandage 1953; Humphreys 1975), AE And (Humphreys 1975), Var 15 (Hubble 1929; Humphreys 1978), Var A-1 (Rosino & Bianchini 1973; Humphreys 1978), and the newly recognized J004526.62+415006.3 (Sholukhova et al. 2015; Humphreys et al. 2015). The four in M33 are Variables B, C, and 2 (Hubble & Sandage 1953; Humphreys 1975) and Var 83 (Humphreys 1978).

These stars plus a few candidate LBVs are listed in Table 1 with their luminosities and temperature estimates for their quiescent state with the corresponding references. LBVs have one important advantage over other supergiants. During the LBV enhanced mass loss state, with the cool, dense wind, the bolometric correction is near zero, allowing us to determine its bolometric luminosity once corrected for interstellar extinction. This is the case for Var B, and Var C and for the new LBV, J004526.62+415006.3. Other luminosities and temperatures in Table 1 are primarily from Szeifert et al. (1996) or Humphreys et al. (2014b). The adopted corrections for interstellar extinction are from Humphreys et al. (2014b). The LBVs and candidates are shown on an HR Diagram in Figure 2

²Var A is now considered a post red supergiant, warm hypergiant (Humphreys et al. 1987, 2006, 2013)

Table 1. LBVs and Candidate LBVs in M31 and M33

Star Name	Sp. Type	Quiescent Temp.	M_{Bol}	Refs ^a	Velocity (km s ⁻¹)	Comment
M31						
AE And	B2-B3	18,000	-9.3 to -9.8	1,2	-250(-213)	A170, H II
AF And	Of/WN	28,000	-10.7	1,2	-274(-280)	...
Var A-1	...	19,000	-10.3:	2	-207(-170)	A42, H II
Var 15	Of/WN	16,000:	-8.5:	2	-243(-212)	A38
J004526.62 +415006.3	...	...	-9.65	2,3	-88(-62) ^b	A45, H II
J004051.59 +403303.0	...	...	...	4	... ^c	A82, candidate
J004425.18 +413452.2	B2-B3	18,000	-8.0	2	-89(-84) ^d	A4, A9, candidate
M33						
Var B	B0-B2	22,000	-10.4	1,2	-147(-110) ^e	A142
Var C	B1-B2	20,000	-9.8	2,5	-121(-112)	H II
Var 83	...	32,000:	-11.1	1,2	-165(-161)	A101, A103, H II
Var 2	Ofpe/WN9	29,500	-10.1	2,6	-208(-193) ^f	A100
V532	WN8	42,000:	-10.4 to -10.7	7	-214(-208) ^g	A89 candidate
UIT 008	Of/WN	33,000	-10.7	2	...	A27, NGC 288, candidate
B526NE	...	...	...	2	-184(-163) ^h	A101, candidate

^a(1)Szeifert et al. (1996),(2)Humphreys et al. (2014b),(3)Humphreys et al. (2015),(4)Sholukhova et al. (2015),(5)Humphreys et al. (2014a),(6)Neugent & Massey (2011),(7)Sholukhova et al. (2011)

^bThe star was in eruption. Only two [Fe II] lines.

^cNo [Fe II] lines.

^dAbsorption lines.

^eNo [Fe II] lines in the 2010 spectrum. The velocity is from the [N II] and the [Fe III] lines. Two [Fe II]lines in the 2013 spectrum give -142 km s⁻¹.

^fNo [Fe II] lines. The velocity is from [N II].

^gNo [Fe II] lines. The velocity is from the [N II] and the [Fe III] lines .

^hIts close neighbor to the SW has a velocity of -179.

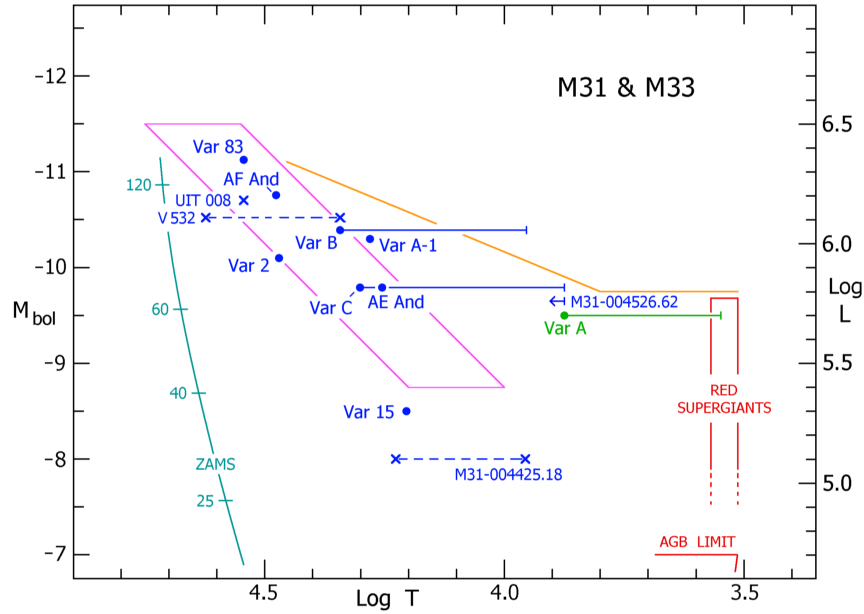


Fig. 2.— A schematic HR Diagram for the LBVs and candidate LBVs in M31 and M33 discussed in the text. The apparent transits in the HR Diagram during the LBV maximum light or cool, dense wind stage are shown as straight blue lines. The LBV/S Dor instability strip is outlined in pink and the empirical upper luminosity boundary is shown in orange.

Most of the known and candidate LBVs in these galaxies are in known stellar associations mapped previously by Hodge (1981) for M31 and by Humphreys & Sandage (1980) in M33 and a few are also in or near H II regions. The association designation (A) and number from these references are given in the comments column in Table 1. To compare their space distribution with the luminous star populations in these galaxies, we show images in the Appendix of their environments made from the Local Group Galaxy Survey (Massey et al. 2006). The LBVs and representative nearby stars listed in Table 2 are identified in each image. Although spectra are not available for these neighboring stars, their magnitudes and colors included in Table 2 indicate that most are hot stars or other supergiants. We use the Q-method (Hiltner & Johnson 1956; Johnson 1958) to estimate the intrinsic B-V colors, color excess, and visual extinction (A_v) with $R = 3.2$ for the candidate OB-type stars in Table 2. Their absolute visual luminosities, M_v are determined using distance moduli of 24.4 mag and 24.5 mag for M31 and M33, respectively (Riess et al. 2012; Scowcroft et al. 2009).

2.1. Comments on individual stars

AE And had an LBV eruption that lasted for twenty years when it was the visually brightest star in M31 (Luyten 1928). Recent spectra show significant variability in the strengths of the absorption and emission lines indicating an unstable wind. It is in the outer parts of M31 approximately $10''$ north of A170. Although there is no associated H II region, an arc of emission nebulosity passes through the star (Figure A1). Nearby stars include three hot stars and one possible red supergiant. AE And’s luminosity places it just at the upper luminosity boundary, so it could be a post-red supergiant (RSG).

AF And is in an association of young stars with a neighboring H II region (Figure A1), although this stellar grouping was not included in the Hodge catalog.

Var A-1 is in A42 with an associated H II region (Figure A2). The closest star is a luminous hot star, possibly a late O star, based on its colors.

Var 15 is a “less luminous” LBV and therefore less massive than the other LBVs in M31. It is in A38 and just to the east of a major dust lane (Figure A2). The closest star is red and may be a red supergiant. V15’s luminosity and temperature in Table 1 are estimated from its current SED (Humphreys et al. 2014b). From 1992 to 2001 it got both fainter, by about one magnitude in V, and bluer (Fig. 9 in (Humphreys et al. 2014b)). The color change suggests that it has gotten hotter.

The new LBV, *J004526.62 +415006.3 (M31-004526.62)*, is in A45 with an associated H II region (Figure A4). The three closest stars are all hot stars, probable late O-type supergiants based on their colors and luminosities.

J004051.59 +403303.0 is a candidate LBV (Massey et al. 2007; Sholukhova et al. 2015). It is in the large association A82 in the outer SE spiral arm (Figure A3). Three of the nearest stars are luminous hot stars. Our spectrum from 2013 (Gordon et al. 2016) shows prominent asymmetric Balmer emission lines with P Cyg profiles and Fe II emission lines with strong P Cyg absorption features. The strengths of the Ca II H and K absorption lines and the Mg II 4481 and He I 4471 lines suggest an early A-type supergiant. Although, it has been called an LBV or LBV candidate it could also be a warm hypergiant (Humphreys et al. 2013; Gordon et al. 2016).

J004425.18 +413452.2 is a potentially interesting star. It shows spectral variability reminiscent of LBVs, but its luminosity is well below the S Dor instability strip (Humphreys et al. 2014b). It is in a spiral arm between the associations A4 and A9 (Figure A3). The nearest stars all have intermediate colors typical of yellow supergiants consistent with this star’s lower mass and probable post-RSG status.

Var B in M33 has been observed in a recent eruption (Szeifert et al. 1996; Massey et al. 1996), and consequently has a well-determined luminosity. It is in A142 near the center of M33 (Figure A5). One of the closest objects, marked *d*, may be a compact H II region based on its point-source appearance and very bright H α magnitude. Three additional nearby hot stars have the colors of late O and early B-type supergiants.

Var C has been observed in several maximum light episodes (Burggraf et al. 2015) since its initial discovery. It entered another maximum light phase in 2013 (Humphreys et al. 2014a). A period analysis of its light curve suggests possible semi-periodic behavior of 42.4 years (Burggraf et al. 2015). Nearby stars include three hot supergiants and a possible RSG (Figure A5).

Var 83 is a luminous LBV in the prominent southern spiral arm in M33 situated between two large associations, A101 and A103. It is surrounded by several prominent nebulous arcs, and three nearby neighbors have the colors of O stars and early B-type stars (Figure A6).

Var 2 is near A100, 10'' above its northern boundary, and was classified Ofpe/WN9 by Neugent et al (2012). It is surrounded by nebulosity (Figure A6) and the brightest nearby star (a) has the colors of an A-type supergiant while three nearby faint stars have the colors of O-type stars and are likely main sequence stars based on their luminosities.

M33-V532 = GR 290 also known as Romano’s star, has been considered an LBV or LBV candidate by several authors. Its spectrum exhibits variability from WN8 at minimum to WN11 at visual maximum (Sholukhova et al. 2011; Polcaro et al. 2011) with a corresponding apparent temperature range from about 42000 K to 22000 K (Sholukhova et al. 2011). But it is not known to show the spectroscopic transition from a hot star to the optically thick cool wind at visual maximum that that is characteristic of the LBV/S Dor phenomenon. It may either be in transition to the LBV stage or if it may be in a post-LBV state (Polcaro et al. 2011; Humphreys et al. 2014b). It is included here as a candidate LBV. It is in the outer parts of M33 about 30'' east of A89 (Figure A7). The nearest star (a) has the colors of an O-type main sequence star.

UIT 008 is another candidate LBV (Humphreys et al. 2014b). It has the spectrum of an Of/WN star and an unusually slow wind like the LBVs. Its high temperature and luminosity place it near the top of the S Dor instability strip. It is located in A27 and its associated H II region NGC 588 which contains several luminous O stars and WR stars.

B526 = UIT 341 = M33C-7292 has been considered an LBV candidate (Clark et al. 2012), but it is actually two stars separated by less than 1''. Its published spectra are all likely composite. A recent long slit spectrum observed with the LBT/MODS (Humphreys et al. 2016) clearly separates the two stars and shows that the northeast component has an emis-

sion line spectrum often associated with LBVs with strong H emission with P Cygni profiles plus Fe II and [Fe II] emission. We therefore consider this object’s northeast component a candidate LBV (B526NE). It is in the large A101 association with numerous nearby luminous stars (Figure A7). We classify its close neighbor to the southwest as a B5 supergiant (Humphreys et al. 2016).

Table 2. M31 and M33 LBV Neighbors

Star Name	V(mag)	B–V (mag)	U–B (mag)	(B–V) ₀ (mag)	M _V (mag)	Comment
M31						
AE And	(J004302.52+414912.4)					
a J004302.93+414902.8	21.04	-0.05	-1.07	-0.34	-4.3	
b J004301.58+414850.1	19.59	-0.01	-1.03	-0.34	-5.9	
c J004302.17+414851.8	20.53	-0.21	-1.08	-0.31	4.2	
d J004304.02+414849.1	19.49	1.57	...	...		RSG?
AF And	(J004333.09+411210.4)					
J004331.95+411204.8	19.89	1.00	-0.55	...	...	YSG?
J004331.82+411204.9	20.27	-0.04	-0.86	-0.27	-4.9	
J004331.85+411218.4	20.28	0.62	0.34	...	...	YSG?
J004331.57+411207.8	20.85	0.09	-0.79	-0.28	-4.7	
J004332.69+411219.7	19.39	1.51	1.18	...	...	RSG?
Var A-1	J004450.54+413037.7)					
a J004450.89+413037.6	19.99	0.15	-0.81	-0.30	-5.9	
Var 15	(J004419.43+412247.0)					
a J004419.45+412244.3	20.86	1.48	...	...	...	RSG?
J004526.62+415006.3						
a J004526.68+415009.1	19.49	0.18	-0.80	-0.31	-6.5	
b J004527.21+415005.7	18.78	-0.03	-0.99	-0.32	-6.6	
c J004527.08+415004.3	20.08	-0.01	-0.93	-0.31	-5.3	
J004051.59+403303.0						candidate
a J004051.70+403253.8	18.80	0.58	-0.57	-0.33	...	YSG?
b J004052.28+403252.2	20.52	0.11	-1.00	-0.35	-5.4	
c J004051.47+403247.6	20.59	0.11	-0.41	-0.16	-4.7	
J004425.18+413452.2						candidate
a J004424.70+413445.3	20.69	0.64	0.33	...	...	YSG
b J004424.35+413509.1	20.80	0.39	0.14	...	...	YSG
M33						
Var B	(J013349.23+303809.1)					
a J013348.82+303815.5	19.78	0.35	-0.49	...	...
b J013348.81+303816.7	21.70	-0.21	-0.63	...	...
c J013348.80+303813.2	20.12	0.68	0.35	...	...	YSG
d J013349.43+303800.1	19.14	-0.17	0.28	...	...	compact HII?
Var C	(J013335.14+303600.4)					
a J013334.97+303601.1	19.31	-0.20	-1.16	-0.33	-5.6	
b J013335.40+303554.7	18.48	0.10	0.05	...	...	YSG?
c J013335.11+303604.2	20.09	-0.12	-1.11	-0.34	-5.1	
d J013335.30+303607.9	19.86	0.45	-0.38	...	...	YSG?
d J013335.53+303555.3	19.71	1.79	1.34	...	...	RSG?
Var 2	(J013418.36+303836.9)					
a J013418.20+303847.1	19.72	0.00	-0.07	-0.02	-4.8	
b J013418.47+303831.5	20.69	0.00	-0.93	-0.31	-4.8	
c J013418.34+303830.5	21.03	-0.10	-1.09	-0.34	-4.2	
d J013418.22+303826.6	20.43	-0.11	-1.04	-0.32	-4.7	
Var 83	(J013410.93+303437.6)					
a J013411.02+303443.6	20.63	-0.08	-0.78	-0.24	-4.4	

Table 2—Continued

Star Name	V(mag)	B–V (mag)	U–B (mag)	(B–V) ₀ (mag)	M _V (mag)	Comment
b J013410.47+303434.3	20.23	0.01	-1.03	-0.34	-5.4	
c J013410.79+303429.2	20.03	-0.12	-0.85	-0.25	-4.9	
d J013410.95+303445.3	19.08	0.77	0.45	...	...	YSG?
M33-V532 = GR 290	(J013509.73+304157.3)					candidate
a J013509.43+304204.8	21.25	-0.25	-1.12	-0.31	-3.5	
b J013509.66+304146.2	20.82	0.25	0.15	...	...	YSG?
B526NE (M33C-7292)	(J013416.10+303344.9)					candidate
a J013416.01+303337.6	18.67	-0.20	-0.87	-0.24	-6.0	
b J013415.62+303344.7	18.98	-0.09	-0.99	-0.31	-6.2	
c J013415.77+303341.7	18.89	0.10	-0.77	-0.28	-6.8	
d J013415.71+303341.0	18.74	0.51	-0.82	...	...	YSG?

2.2. Spatial Distribution and Kinematics

As we have emphasized, the spatial distribution of the LBVs should be compared with a stellar population of similar evolutionary state, with comparable luminosities and initial masses based on their positions on the HR Diagram. All of the above luminous LBVs and candidates with $M_{Bol} \gtrsim -9.8$ mag, are in associations of luminous stars, some with associated H II regions and emission nebulosity. Their nearby stars in Table 2, for the most part have the colors of early-type stars. One might argue that by comparison AE And looks relatively isolated. With its luminosity range, it could be a post-RSG candidate and its association with less luminous stars would be expected. The WR variable, M33-V532 is likewise in the outerparts of M33, but near an association with several early type stars.

In the Smith and Tombleson model not only have the LBVs gained mass from a companion, but they have been “kicked” or moved away from their place of origin after the supernova explosion of their more massive companion. In that case, we would expect some of the LBVs to have high velocities compared to their expected velocity in the parent galaxy. They would be runaway stars.

Their radial velocities are in Table 1 together with the expected velocity, in parentheses, at their positions in M31 and M33. The absorption lines in LBVs show considerable variability due to their variable winds. We use the velocities measured from the centroid of [Fe II] and [N II] lines to estimate their systemic velocities. These lines are formed in the low density outer parts of the wind and are not affected by P Cygni absorption. The expected velocities were calculated following the prescription and fit to the rotation curves from Massey et al. (2009), Drout et al. (2009), and Drout et al. (2012), for the yellow and red supergiants in M31 and M33.

Most of the LBVs have velocities within 40 km s^{-1} of the expected velocity based on the rotation curve. This is consistent with and within the velocity range used by Drout et al. (2009, 2012) to decide on membership of the yellow supergiants in M31 and M33. The velocities for runaway stars depend on the orbital parameters. Based on some of the models, the velocities are expected to be 100 to 200 km s^{-1} and higher (Tauris & Takens 1998). Thus, none of the LBVs or candidates can be described as a runaway star.

3. The Milky Way LBVs

There are very few confirmed LBVs in the Milky Way due to the infrequency of the LBV eruption and of course to the uncertainty in the distances. Smith and Tombleson list 10

LBFs and candidate LBFs and discuss some of the better studied examples. A few deserve some comments and cautionary remarks. As has been acknowledged for some time, the giant eruption η Car is clearly associated with a population of luminous massive stars including several O3-type stars (Davidson & Humphreys 1997). At its presumed initial mass of 150 - 200 M_{\odot} , it is at most about 2 – 3 million years old and has not have moved far from its place of birth.

Smith and Tombleson emphasize that most of the other Galactic LBFs are relatively isolated from O stars. But most are also much less massive and will be older. For example, the well-studied, classic stellar wind star, and survivor of a giant eruption, P Cygni is in the Cyg OB1 association. At its distance, the two nearest B-type supergiants of similar temperature and luminosity are about 30 pc away. The same is true of an O star. At its position on the HR Diagram, P Cyg had an initial mass of ≈ 50 - 60 M_{\odot} and is past core H-burning with a current mass of 23 to 30 M_{\odot} (Lamers et al. 1983; Pauldrach & Puls 1990). It is therefore at least 4 - 5 $\times 10^6$ years old based on models by e.g., Ekstrom et al. (2012), with and without rotation. With a velocity dispersion of 10 km s $^{-1}$ for the extreme Population I, P Cyg will have moved 35 - 44 pc or more. So its spatial separation from similar stars is what would be expected.

AG Car is a well-studied classical LBF. At its high luminosity and presumed initial mass of $\approx 80 M_{\odot}$, one would expect to find an associated population of massive stars. Smith and Tombleson argue that there are no nearby O stars. However, at its large kinematic distance of ≈ 6 kpc (Humphreys et al. 1989; Groh et al. 2009), AG Car must be compared with the stellar population at the same distance. Since our line of sight to AG Car at $l = 289^{\circ}$, is directly down the Carina spiral arm, the cataloged O stars are most likely in its foreground.

HR Car is in a similar situation at ~ 5 kpc in the Carina arm (van Genderen et al. 1991). HR Car, HD 160529, and HD 168607 are confirmed LBFs, but belong to the less luminous, less massive group of LBFs with ages of roughly 6 million years or more; enough time for them to move 30 to 100 pc away from their original locations even at low random speeds. We would not expect them to be closely associated with O stars.

In all cases these stars need to be compared with stars at the same distance and in the same part of the HR diagram. That is of course the advantage of studying these stars in nearby galaxies and especially in the Magellanic Clouds.

4. The LBVs in the Magellanic Clouds

Smith and Tombleson included nineteen stars in the Magellanic Clouds in their analysis. However, six of the LMC stars in their list are neither LBVs nor candidates. This does not mean that these stars, described below, are not interesting or that someday they may be shown to have LBV characteristics, but they should not be included in a survey to set limits on the spatial distribution of the known LBVs. The six confirmed LMC LBVs (S Dor, R71, R127, R143, R110, R85) and four candidates (S61, S119, Sk -69°142a, Sk -69°279) are listed in Table 3 with their observed parameters. They also list three stars in the SMC, but R40 is the only confirmed LBV/S Dor variable (Szeifert et al. 1993). The very luminous HD 5980 is a complex triple system that may be an example of a giant eruption as we describe below. R4 is a B[e] star. The confirmed LBVs are shown on an HR Diagram in Figure 3. The three most luminous LBVs, R127, S Dor and R143, are the classical LBVs (Humphreys & Davidson 1994), and the remaining four belong to the less luminous group.

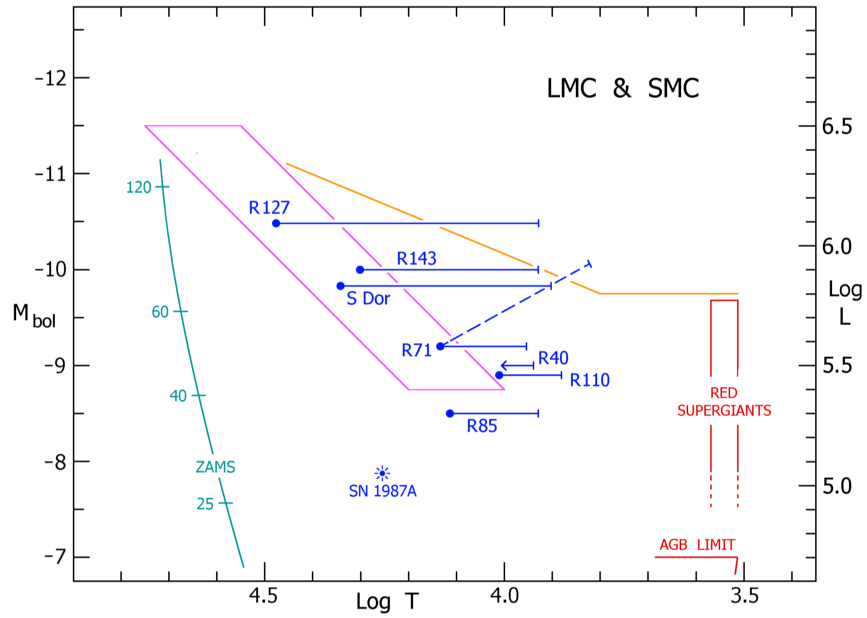


Fig. 3.— A schematic HR Diagram for the LBVs and candidate LBVs in the LMC and SMC discussed in the text. The symbols and colors are the same as in Figure 2.

Table 3. LBVs and Candidate LBVs in the Magellanic Clouds

Star Name	Sp. type	Quiescent Temp.	M_{Bol}	Refs ^a	Dist(pc)	Velocity(km s ⁻¹)	Comment
LMC							
S Dor	B I	20,000 – 25,000	-9.8	1,2	12	296(13)	N119
R127 (HDE 269858f)	Ofpe/WN9	~ 30,000	-10.5	1,3	4	276(13)	N135
R143	O9.5/B1:	25,000:	-10.0	4	4.5	249–286(13)	N157
R71 ^b (HDE 269006)	B5:I	13,600	-9.2	5,6	387	196(13)	
R110 (HDE 269662)	B6 I	10,250	-8.9	7	244	248(14)	N135
R85 (HDE 269321)	B5Iae	13,000:	-8.5	8	22	292(14)	N119
S61 (Sk 67°266)	WN11h	27,600	-9.7	9	125	294(15)	candidate
S119 (HDE 269687)	WN11h	27,000	-9.8	9	302	156(16)	candidate
Sk -69°142a (HDE 269582)	WN10h	22,000	-9.7	9	78	...	candidate
Sk -69°279	O9f	30,300	-9.7	10	60	...	candidate
SMC							
HD 5980	WN4 + ?	45,000–60,000:	-11.5:	11	21	...	giant eruption
R40 (HD 6884)	B8 Ia	12,000	-9.4	12	122	181(14)	

^a(1)Stahl & Wolf (1986),(2)Leitherer et al. (1985),(3)Stahl et al. (1983),(4)Parker, et al. (1993),(5)Wolf et al. (1981),(6)Mehner et al. (2013),(7)Stahl et al. (1990),(8)Massey et al. (2000),(9)Crowther & Smith (1997),(10)Conti et al. (1986),(11)Koenigsberger et al. (2014),(12)Szeifert et al. (1993),(13)Munari et al. (2009),(14)Feast et al. (1960),(15)Ardeberg et al. (1972), (16)Weis et al. (2003a)

^bThe parameters derived for R71 depend on the adopted foreground extinction. The analysis of its previous S Dor maximum light by Wolf et al. (1981) used the minimum foreground value of 0.15 mag for the LMC. Here we use adopt A_V of 0.37 mag, see Mehner et al. (2013), which yields an M_{Bol} of -9.2 mag for its 1970-77 eruption. During its current large eruption, R71 has actually increased in luminosity.

4.1. The LBV Candidates in the LMC and SMC

The properties of the four candidates and the six excluded stars in the LMC plus HD 5980 and the candidate R4 in the SMC are described here with our reasoning for their inclusion or not in our analysis.

S61 (= Sk -67°266) was classified O8Iafpe by Bohannan & Walborn (1989) but later revised to WN11h by Crowther & Smith (1997). No S Dor type variability has been observed and its wind speed of 900 km s^{-1} (Wolf et al. 1987) is much higher than observed for confirmed LBVs in quiescence (Humphreys et al. 2014b), although Crowther & Smith (1997) derive a terminal velocity of 250 km s^{-1} . S61 has an expanding circumstellar nebula (Weis 2003b) similar to the nebulae associated with some LBVs. Primarily for that reason it is included as an LBV candidate.

S119 (= HDE 269687) is an Ofpe/WN9 star (Bohannan & Walborn 1989) or WN11h (Crowther & Smith 1997) with the low wind velocity, 230 km s^{-1} typical of LBVs in quiescence, and an expanding circumstellar nebula (Weis et al. 2003a). But Weis et al. (2003a) also find that the center of the expansion has a velocity of 156 km s^{-1} , rather low for membership in the LMC. The possibility that S119 may be a runaway is discussed later. It has not been observed to show S Dor type variability, and is included here as a candidate LBV.

Sk -69°142a (= HDE 269582) is another late WN star (WN10h, Crowther & Smith (1997)), a class of stars associated with some LBVs in quiescence. It is a known variable with small light variations on the order of $\pm 0.2 \text{ mag}$ (van Genderen & Sterken 1996), but does not have a circumstellar nebula.

Sk -69°279 is classified as an O9f star (Conti et al. 1986) with a large associated circumstellar nebula (Weis et al. 1995, 1997; Weis & Duschl 2002). It is on that basis that we consider it a candidate LBV.

LMC Non-LBVs:

R81 (= HDE 269128 = Hen S86) was initially considered an example of S Dor variability (Wolf et al. 1981), but it was soon shown to be an eclipsing binary (Stahl et al. 1987). This analysis and conclusion is confirmed in the more recent paper by Tubbesing et al. (2002). For this reason it was not included in the review by Humphreys & Davidson (1994). R81's spectroscopic and photometric variability are tied to its orbital motion. It is not an LBV or a candidate.

MWC 112 (= Sk -69°147) is an F5 Ia supergiant (Rousseau, et al. 1978). It has not been considered an LBV candidate, although it has been confused with HDE 269582 discussed above, see van Genderen & Sterken (1996); Humphreys & Davidson (1994).

R126 (= HD 37974) is a B[e]sg star (Lamers et al. 1998; Zickgraf et al. 1985) similar to the classic S18, and has not been considered an LBV or candidate LBV in the literature.

R84 (= HDE 269227) has a composite spectrum with an early-type supergiant plus an M supergiant (Munari et al. 2009). It has been suggested to be a dormant LBV (Crowther et al. 1995), but the various conflicting descriptions of this star which have included reports of TiO bands, are now attributed to its composite nature (B0 Ia + M4 Ia, Stahl et al. (1984)). If this is a physical pair it is an important star since so few M supergiants are known binaries.

Sk -69°271 (= CPD -69°5001) has been classified as a B4 I/III star (Neugent & Massey 2011). It is associated with an arc of H α emission (Weis et al. 1997) and is considered to be a possible X-ray binary (Sasaki et al. 2000). It has not been suggested to be an LBV or candidate in the literature. Its luminosity, based on its spectral type and extinction (Neugent & Massey 2011), of $M_{Bol} \approx -7.90$ mag, places it below the LBV/S Dor instability strip.

R99 (= HDE 269445) can best be described as peculiar. It is classified as an Ofpe/WN9 star (Bohannon & Walborn 1989). Although it shows spectral and photometric variability, the amplitude is very small. Crowther & Smith (1997) emphasize its peculiar spectrum and variability. Its high wind velocity of 1000 km s⁻¹ argues against an LBV in quiescence. Although it is associated with emission from a nearby H II region, Weis (2003b) concludes that there is no circumstellar nebula like those associated with some LBVs and candidates.

A Giant Eruption Candidate and a Non-LBV in the SMC

HD 5980 is a complex triple system with two luminous hot stars in a short period eclipsing binary ($P_{AB} = 19.3^d$). Star B is considered to be an early-type WN star, and the third star(C) is an O-type supergiant which may also be a binary (Koenigsberger et al. 2014). In 1994, HD 5980 experienced a brief 3.5 mag brightening that lasted about 5 months. At maximum, the absorption line spectrum was described as B1.5Ia⁺ (Koenigsberger et al. 1996), but Moffat et al. (1998) later classified it as WN11. It did not produce the LBV/S Dor cool wind at maximum. In that respect it is reminiscent of M33-V532. Given its brightening and short duration however, HD 5980 can be better described as a giant eruption. Nevertheless numerous authors describe it as an LBV. For that reason we include it in Table 3, but with the above caveat.

R4 is a spectroscopic binary (Zickgraf et al. 1996) with an early B-type supergiant plus an early A-type supegiant. The hot star is described as a B[e] star with T_{eff} of 27,000° and $M_{Bol} = -7.7$ mag which places it below and well outside the S Dor instability strip. Its LBV nature has not been established, and subsequent papers treat it as a B[e] star.

4.2. The Spatial Distribution and Kinematics of the Magellanic Cloud LBVs

Here we reassess the Smith and Tombleson analysis of spatial correlations in the LMC and SMC. For each star in a set, e.g. WN stars, red supergiants, or LBVs, they measured the projected distance $D1$ to the nearest O-type star and plotted the cumulative fraction of the stars in that set that have $D1$ less than a given value. This is illustrated in Figure 4 where we reproduce their Magellanic sample from their Table 1 together with the late O-type stars, WN stars, and red supergiants. The O-type stars, for example, tend to exist in groups, so naturally they have small values of $D1$. We would conclude from this figure that the red supergiants have a spatial distribution uncorrelated with O stars. The stars in the Smith and Tombleson sample fall in between.

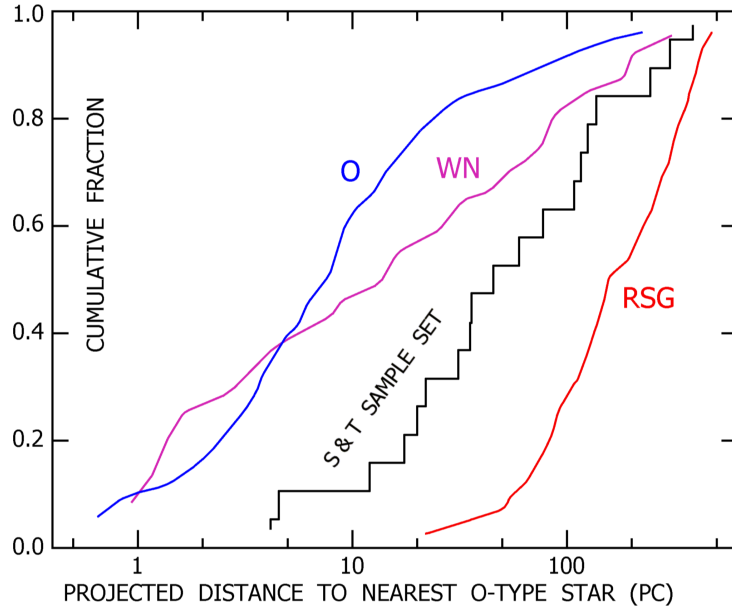


Fig. 4.— The cumulative fraction versus the projected distance to the nearest O -type star for the Magellanic Cloud sample from Smith & Tombleson (2015) based on their figure. The distributions for the late O-type stars, WN stars, and red supergiants are shown for reference.

We repeat this analysis for the seven confirmed LBVs in Table 3. The seven stars discussed in §4.1 that have no clear relation to LBVs are removed, and the four “candidates” are discussed below. We show the cumulative distributions for the *classical* and *less luminous* LBVs in Figure 5, plotted respectively, as LBV1 and LBV2³. The three most luminous stars

³Set LBV1 consists of R127, R143, and S Dor; no additional classical LBVs have been found in the LMC and SMC since 1994. Set LBV2 includes R71, R110, R85, and R40.

(LBV1) in the sample were originally identified as classical LBVs by Humphreys & Davidson (1994), and were not merely chosen in relation to Smith and Tombleson’s arguments. They have an average $D1$ of only 7 pc, and, as Figure 5 shows, their distribution is statistically indistinguishable from the late O-type stars. The four stars in LBV2 are all substantially fainter than the $M_{\text{bol}} \approx -9.7$ criterion. As expected for these less massive, highly evolved objects, they parallel the RSG distribution in Figure 5. Formal statistical tests are doubtful for such a small sample; but if one attempts to apply any such test (e.g., Kolmogorov-Smirnov), the result is excellent consistency between set LBV2 and the RSG distribution. This is obvious in the figure.

Moreover, elementary statistics support the distinction between classical and less luminous LBVs. Among the 7 confirmed LBVs, the three classical LBVs have the three smallest values of $D1$. The ab initio probability of this outcome would be 2.9% if all seven represent the same population; so, in this sense, the difference between the two classes is significant with a 97% confidence. Two aspects of this statement are worth noting. (1) Given only seven objects, 97% is the highest confidence level that can be attained without additional information.⁴ 2) In terms of standards for judging scientific evidence, the above result is useful *because it was not known at the time when the two classes of LBVs were defined*.

Just as important, their velocities do not suggest that any of the LBVs are runaways or have exceptionally high velocities. Their heliocentric velocities are included in Table 3 with the references. The emission line velocities are given for the RAVE measurements (Munari et al. 2009) except for R143⁵. The published average velocities for the Magellanic Clouds range from 262 - 278 km s⁻¹ for the LMC and from 146 - 160 km s⁻¹ for the SMC (Richter et al. 1987; McConnachie 2012). The LBV velocities are all consistent with their membership, and for the LMC stars, with their position based on the H I rotation curve available at NED (from Kim et al. (1998)). The only exception is the candidate LBV, S119 with a possible systemic velocity based on the center of its expanding nebula (Weis et al. 2003a) that is much lower than expected at its position in the LMC. Thus S119 is a candidate

⁴ The Kolmogorov-Smirnov test is inappropriate here for two reasons: The $D1$ values of sets LBV1 and LBV2 do not overlap, and the sample size is too small. The t test for two finite samples with unequal variance formally gives a confidence level of about 99% for the distinction between LBV1 and LBV2, but this entails extra assumptions that are too complicated to review here. A detail in our reasoning is that $D1$ is expected to be smaller in set LBV1, as observed, and not larger. The main point is that elaborate statistical analyses are not worthwhile with such a small sample size. For comments about statistical testing in general, see

<https://asaip.psu.edu/Articles/beware-the-kolmogorov-smirnov-test/>.

⁵The absorption line velocities are also given in Munari et al. (2009)

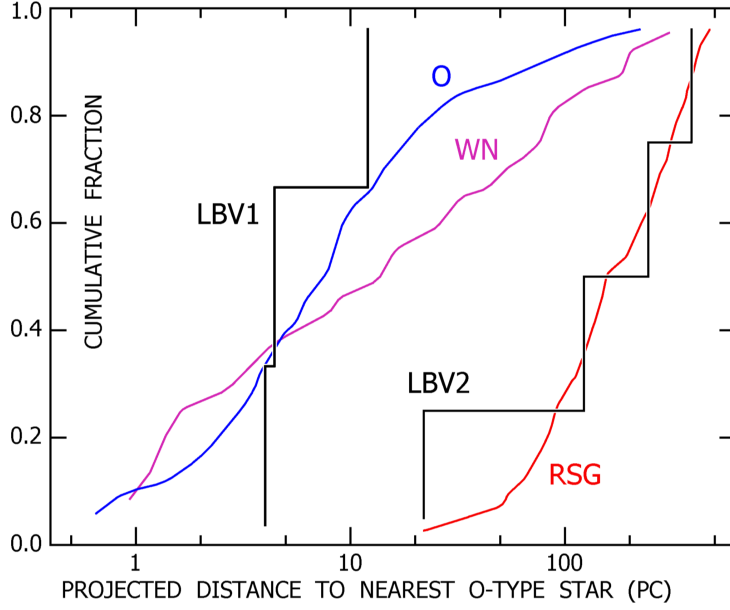


Fig. 5.— The cumulative fraction versus the projected distance to the nearest O -type star for the *classical* LBVs (LBV1) and *less luminous* LBVs (LBV2) in the Magellanic Clouds.

for a runaway star.

In addition, a runaway star with a high velocity would be expected to alter the morphology of its circumstellar ejecta, the LBV nebula. Runaway stars are commonly known to have an arc-like bow shock nebula due to interaction with the interstellar medium (Brown & Bomans 2005). The stars in M31 and M33 are too distant to search for bow shocks, but several confirmed LBVs and candidates in the Milky Way and LMC have associated circumstellar nebulae that are either spherical or bipolar in shape (Weis 2011). They are not bow shocks. The only nebula that has a signature, an embedded arc in the surrounding nebulosity, that could be attributed to a bow shock is S119 which may be a runaway.

The distribution of the four LBV candidates in the LMC (Figure 6) interestingly follows that of the less luminous LBVs. Three of the four are considered candidates because of their circumstellar nebulae. The origin of their very extended ejecta may be a prior giant eruption or numerous earlier S Dor-like events, but their low expansion velocities ($14\text{--}27\text{ km s}^{-1}$) are a puzzle compared with the outflow velocities of LBV winds and giant eruptions⁶. They may be due to deceleration with the ISM or the product of mass loss in a previous state with lower ejection velocities. Their published luminosities are very similar and except for

⁶The nebulae associated with Milky Way LBVs have expansion velocities of $50\text{--}75\text{ km s}^{-1}$.

Sk -69°279, they lie in or near the LBV instability strip. Based on their position on the HR Diagram, they may be post-RSGs or given their rather high luminosities, former warm hypergiants like IRC +10420 or Var A in M33.

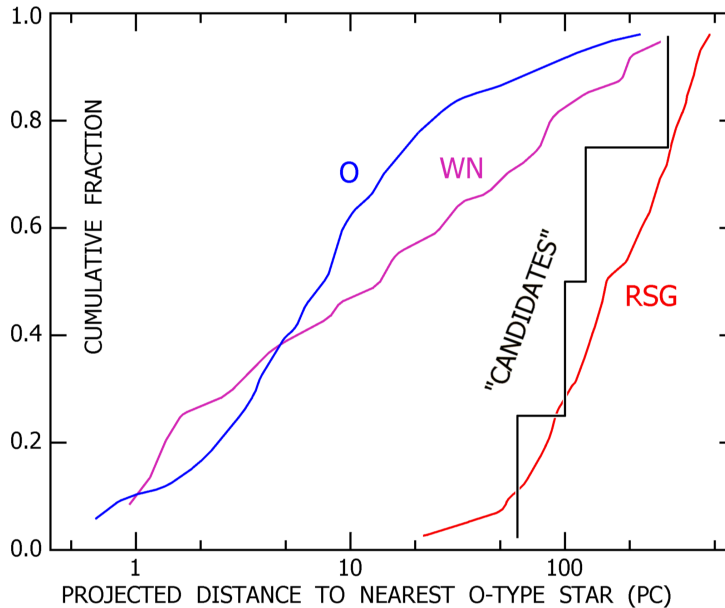


Fig. 6.— The cumulative fraction versus the projected distance to the nearest O -type star for the four candidate LBVs in the LMC.

5. Concluding Remarks

In M31 and M33 we conclude that except possibly for AE And which may be a post-RSG, the LBVs and candidates are associated with luminous young stars and supergiants appropriate to their luminosities and positions on the HR diagram. Their measured velocities are also consistent with their positions in their respective galaxies. There is no evidence that they are runaway stars that have moved away from their place of origin.

In the Magellanic Clouds, separating the LBVs by luminosity removes the apparent isolation of the LBVs claimed by Smith and Tombleson. The more luminous and more massive, classical LBVs have a distribution similar to the late-type O stars and the WN stars, while the less luminous ones have a distribution like the RSGs, an evolved lower mass population of supergiants. In both the Magellanic Clouds and in M31 and M33, none of the sample of 16 confirmed LBVs have high velocities or are candidate runaway stars.

One positive result is especially notable: since the LBV distribution in Figure 5 is

indistinguishable from the red supergiants, evidently the less luminous LBVs are not young. This fact strongly supports the interpretation outlined in Section 1, i.e., those objects have evolved back to the blue in the HR Diagram.

It is not necessary to invoke an exotic explanation such as “kicked mass gainers” from binary systems to explain the Luminous Blue Variables. Some LBVs and candidates are indeed binaries (Rivinius, et al. 2015; Lobel et al. 2013; Martayan et al. 2016), but this binarity contradicts the Smith and Tombleson scenario of the LBV, the primary in these systems, as the mass gainer. Thus the results of our discussion and analysis supports the accepted description of LBVs of all luminosities as evolved massive stars that have shed a lot of mass, whether as hot stars or as red supergiants, and are now close to their Eddington limit.

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A. The LBV Environments in M31 and M33

The blue and $H\alpha$ images of the LBVs and candidate LBVs shown here are from the Local Group Galaxy Survey (Massey et al. 2006). Their survey used the standard UBVRI filters plus narrow band filters with the Mosaic CCD Camera on the KPNO 4-meter Mayall telescope. The reduced images have a scale of $0.27''$ per pixel. Details of the reductions can be found in the paper and at the LGGS web site. The authors quote 1% to 2% photometry for stars expected to be above $20M_{\odot}$. The dashed grid on the images reproduced here is $10''$. At the distances of M31 and M33, $10''$ is approximately 37 pc.

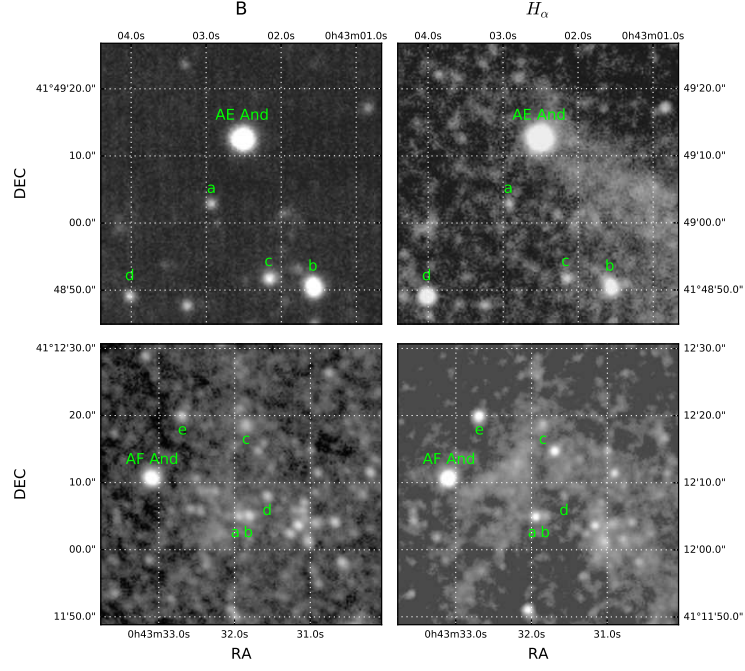


Fig. A1.— The blue and $H\alpha$ images for AE And (top) and AF And (bottom). Note the arc of emission nebulosity near AE And.

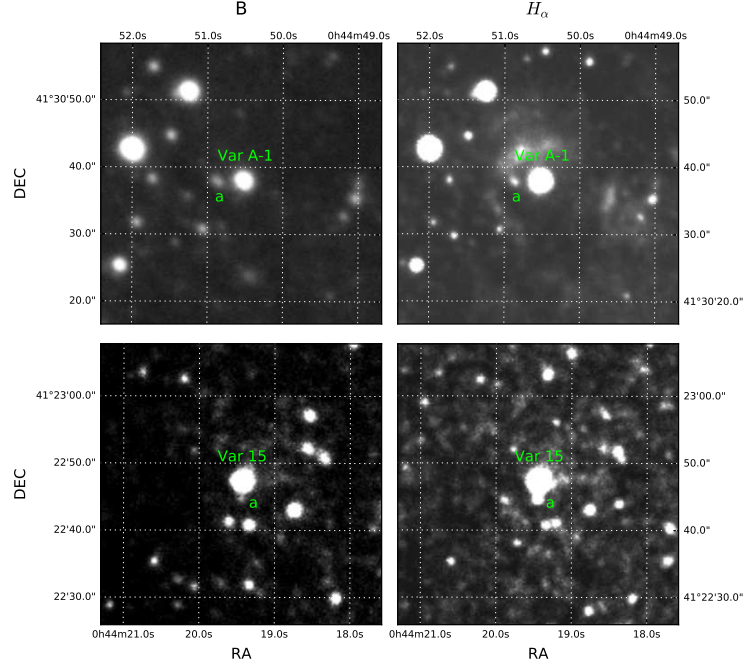


Fig. A2.— The blue and $H\alpha$ images for Var A-1 and Var 15.

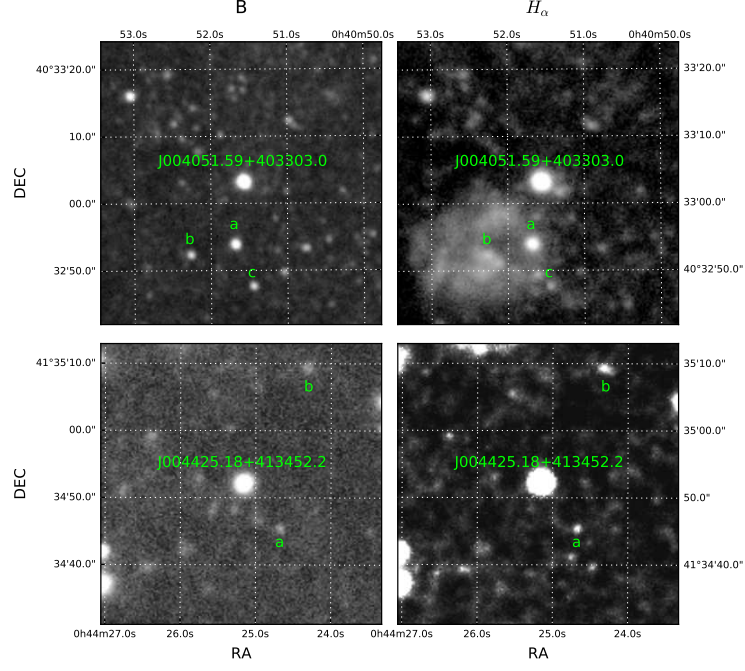


Fig. A3.— The blue and H_α images for J004051.59+403303.0 and J004425.18+413452.2

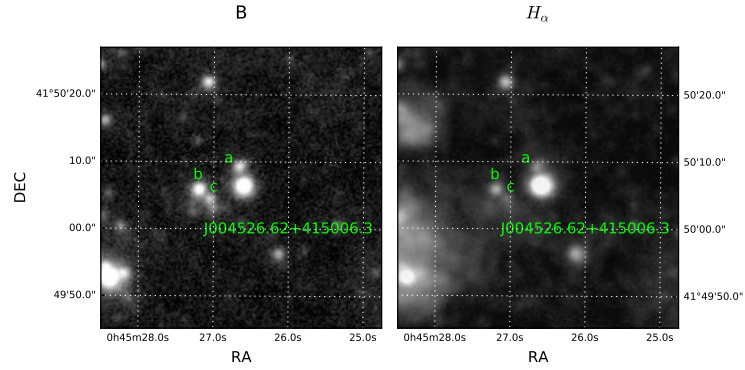


Fig. A4.— The blue and H_α images for J004526.62+415006.3.

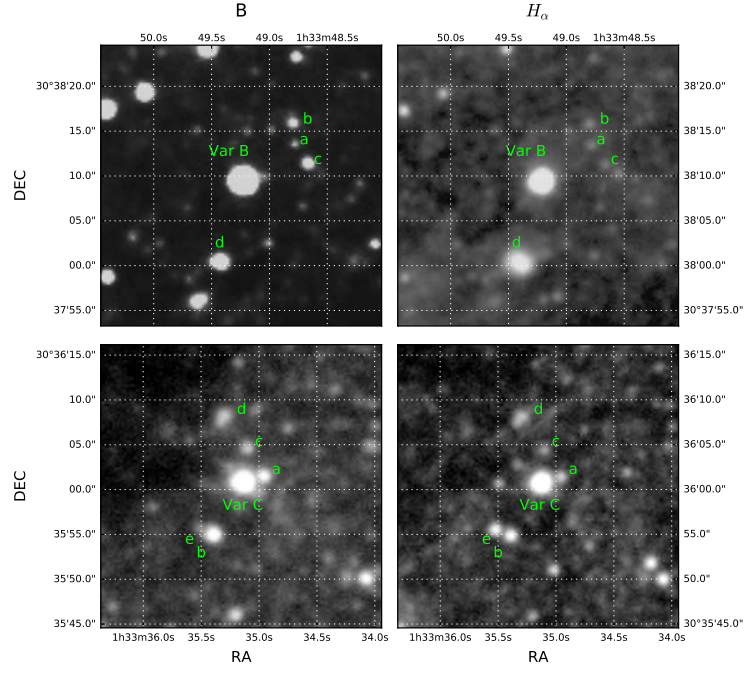


Fig. A5.— The blue and $H\alpha$ images for Var B and Var C.

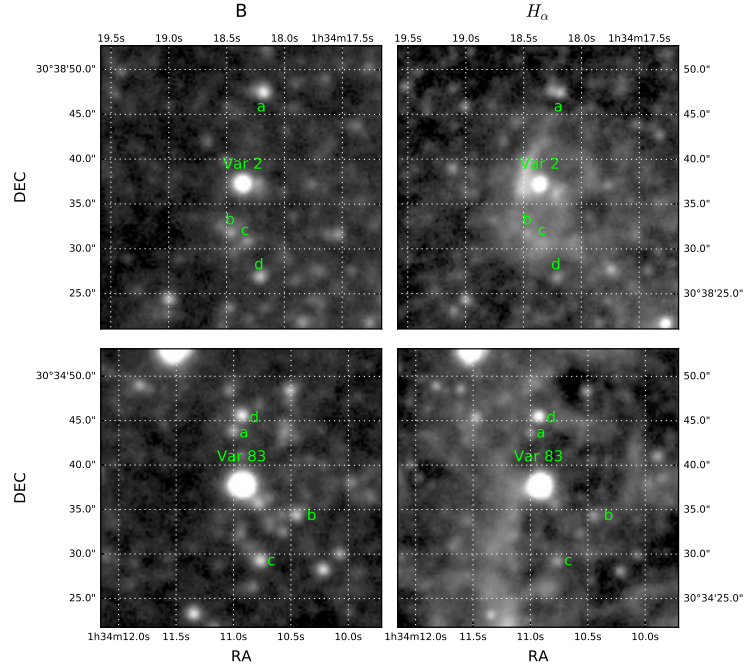


Fig. A6.— The blue and $H\alpha$ images for Var 2 and Var 83.

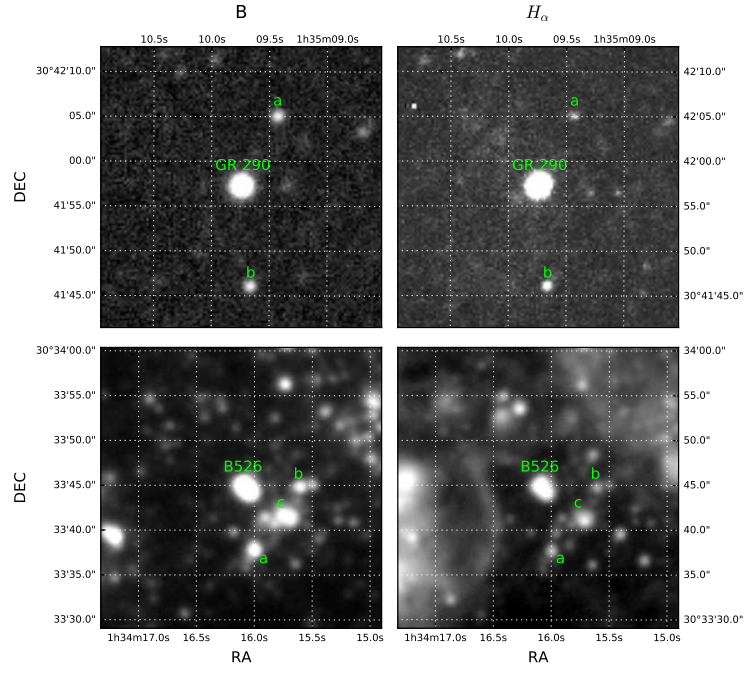


Fig. A7.— The blue and H α images for GR 290 = M33-V532 and B526.

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